Tabernero, Juan and Atchison, David A. and Markwell, Emma L. (2009) ***Aberrations and pupil location under corneal topography and Hartmann-Shack illumination conditions.*** Investigative Ophthalmology & Visual Science, 50(4). pp. 1964-1970.

Aberrations and Pupil Location under Corneal Topography and Hartmann-Shack Illumination Conditions

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Purpose. This study was conducted to determine the magnitude of pupil center shift between the illumination conditions provided by corneal topography measurement (photopic illuminance) and by Hartmann-Shack aberrometry (mesopic illuminance) and to investigate the importance of this shift when calculating corneal aberrations and for the success of wavefront-guided surgical procedures.

Methods. Sixty-two subjects with emmetropia underwent corneal topography and Hartmann-Shack aberrometry. Corneal limbus and pupil edges were detected, and the differences between their respective centers were determined for both procedures. Corneal aberrations were calculated using the pupil centers for corneal topography and for Hartmann-Shack aberrometry. Bland-Altmann plots and paired *t*-tests were used to analyze the differences between corneal aberrations referenced to the two pupil centers.

Results. The mean magnitude (modulus) of the displacement of the pupil with the change of the illumination conditions was 0.21 ± 0.11 mm. The effect of this pupillary shift was manifest for coma corneal aberrations for 5-mm pupils, but the two sets of aberrations calculated with the two pupil positions were not significantly different. Sixty-eight percent of the population had differences in coma smaller than 0.05 μm, and only 4% had differences larger than 0.1 μm. Pupil displacement was not large enough to significantly affect other higher-order Zernike modes.

Conclusions. Estimated corneal aberrations changed slightly between photopic and mesopic illumination conditions given by corneal topography and Hartmann-Shack aberrometry. However, this systematic pupil shift, according to the published tolerances ranges, is enough to deteriorate the optical quality below the theoretically predicted diffraction limit of wavefront-guided corneal surgery. (*Invest Ophthalmol Vis Sci.* 2009;50:1964–1970) DOI:10.1167/iovs.08-2111

The extension of measurement techniques used in astronomy to the field of visual and ophthalmic research has produced an extraordinary revolution in this field. Many novel experiments have been performed, leading to interesting scientific discoveries. In particular, with the combined use of corneal topography (CT) to calculate corneal aberrations[1,2] and Hartmann-Shack (HS) wavefront sensors[3,4] to calculate the whole eye aberration function, internal aberrations of the eye can be estimated by subtraction.[5–7] This issue requires a full understanding of the alignment situation of the eye with respect to measurement instruments to provide the most precise calculation. Generally speaking, CT data are centered on the corneal reflex, which marks the origin of the Placido rings, whereas HS wavefront sensors use the entrance pupil center of the eye as the origin for wavefront calculations. Because of the special characteristics of the ocular alignment and the eccentric foveal position, the corneal reflex will be displaced with respect to the center of the entrance pupil.[8] To avoid errors in internal aberration calculation, researchers re-reference the topography data to the pupil center.

A less analyzed issue when comparing corneal and total aberrations is that under different illumination conditions, pupil center location may change.[9,10] Corneal topography is measured under photopic conditions because of the high luminance of the Placido ring target placed near the eye, whereas HS aberrometry is undertaken at mesopic conditions because the target is small and room lighting is kept low. Typical magnitudes of the misalignment between the two pupil centers are unknown, as are the consequences for determining corneal aberrations. To measure misalignment, a common reference system is required for topography and aberrometry. Such a reference system is the corneal limbus center.[11]

Two important questions are whether significant changes in aberration can be expected by changing pupil center references and, if so, whether any aberration terms are affected more than others. With regard to the second question, it is well known that an optical system with spherical aberration will generate third-order coma as a linear function of pupil decentration,[12] whereas spherical aberration and other higher-order aberration terms should remain relatively insensitive to pupil decentration.

Beyond the calculations of corneal aberrations, pupil decentration has important implications for corneal LASIK surgery.[10] If surgery is performed with centration according to constricted pupils, a decentered ablation pattern expected under low illumination may be responsible for poor optical quality. This effect may be especially important now, when wavefront-guided corneal ablation is becoming a popular surgical treatment.[13] The more aberrations are corrected for an optical system, the more sensitive the system will be to decentration. Tolerance limits to decentration for these treatments may be more affected by these misalignments.

A similar problem may be found in cataract surgery with aspheric IOLs.[14] This kind of implant, designed to correct corneal spherical aberration, is becoming popular.[15] Centration of the IOLs is usually performed under dilated pupils during cataract surgery. A shift in the lateral position of the pupil, when it constricts under normal photopic illumination

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Supported in part by National Health and Medical Research Council Grant 290500 (DA).

Submitted for publication April 2, 2008; revised May 27 and October 13, 2008; accepted February 24, 2009.

Disclosure: **J. Tabernero**, None; **D.A. Atchison**, None; **E.L. Markwell**, None

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Investigative Ophthalmology & Visual Science, April 2009, Vol. 50, No. 4

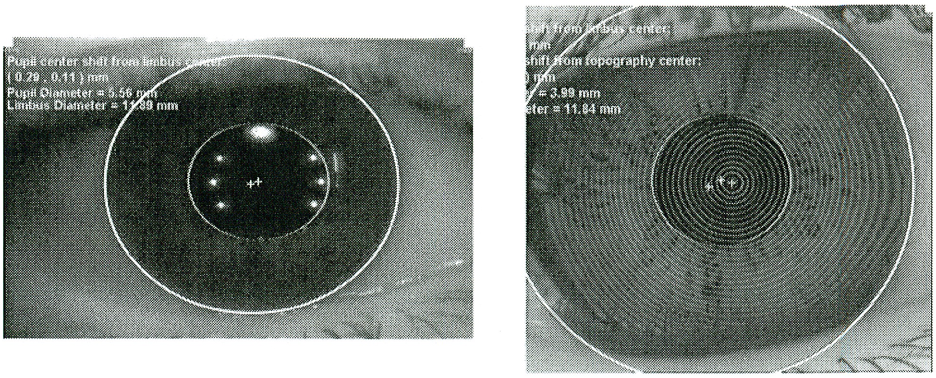

Figure 1. Example of images processed for the same patient. *Right*: topography image with the Placido rings. *Left*: HS alignment camera image (1:1.2 aspect ratio calibrated for the proper calculation).

after surgery, may have implications in postoperative optical quality.

To investigate these questions, we determined pupil center with respect to the limbus center for CT and HS illumination. Based on this, we determined the displacement of the pupil from the corneal reflex and calculated corneal aberrations with respect to pupil center for the two illumination conditions. Changes in aberration between the conditions were analyzed and compared with surgery tolerance limits.

Methods

Subjects and Instruments

This research adhered to the tenets of the Declaration of Helsinki. Sixty-two patients with emmetropia who had no previous ocular abnormalities and who had never undergone ocular surgery were tested. We measured 15 left eyes and 47 right eyes. These measurements were taken into account for subsequent calculations, and the signs were corrected for pupil decentration and horizontal coma (C_1^1) to avoid mirror symmetry. Mean age of the subjects was 42.5 ± 14.7 years (range, 19–69 years). All subjects performed the test session with a natural pupil. Only subjects with pupil diameters larger than 5 mm, when measured with an HS aberrometer, were included. An image of one eye for each subject (containing pupil and limbus margins) was taken with two different instruments, a corneal topographer (Medmont E300; Medmont, Camberwell, Australia) and an HS–based wavefront sensor instrument (COAS; Asclepion-Meditec-Zeiss, Jena, Germany), in their normal operation routines. The image from the topographer also contained the Placido rings used to obtain elevation values, centered on the corneal reflex. The pupil and corneal limbus image from the HS sensor was taken with the alignment camera at the same time the apparatus was used to measure ocular aberrations. Because this camera was used mainly as an aid to alignment, the image was not especially bright, which presented some sensitivity problems and noise. Three images were taken with this instrument to ensure repeatability. However, the topographer camera presented bright, good-quality images, and only one image was taken after a preliminary screening for erroneous images.

Image Processing and Corneal Aberration Calculations

All images were analyzed with ImageJ software (developed by Wayne Rasband, National Institutes of Health, Bethesda, MD; available at http://rsb.info.nih.gov/ij/index.html.). For the topography image, the pupil center and pupil diameter were automatically detected with a routine based on thresholding, binary dilation, and gradient-edge detection. The pupil border was then fitted to a rotated ellipse, and the average of the two semiaxes was taken as the pupil radius. The center of the Placido rings (corneal reflex) was automatically obtained from the maximum value of the convolution of the image with a mask containing two concentric rings whose diameters resembled the two smaller Placido rings. This automatic procedure provided reliable results. Limbus automatic detection presented more complications than pupil and corneal reflex detection. Although some researchers have shown that automatic detection routines are possible (at the expense of a large computational time),[11] we preferred to ensure reliability, and we chose to use a manual routine. After eight points lying over the limbus margin were selected by the operator, a rotated ellipse was fitted using a least-squares routine. This manual procedure was also chosen to analyze pupil and limbus margins for the HS image; image quality did not allow reliable automatic routines. The position of the pupil center with respect to the corneal limbus center and the corneal reflex was calculated using the ellipse centers for both experimental conditions. Figure 1 shows an example of the output of the computer routine developed in this study. On the left side, an image taken with the HS sensor camera (aspect ratio, 1:1.2) is shown with the pupil and limbus edges detected as described. On the right side, an image taken with the CT camera (aspect ratio, 1:1) is shown with the pupil and limbus edges detected along with the Placido ring centration (first Purkinje image).

Corneal aberrations were calculated from the elevation data provided by the topographer. All aberration calculations presented in this article were performed for a 5-mm pupil diameter.

Figure 2 shows how the displacement of the pupil center from the corneal reflex was computed in both conditions. The center of the

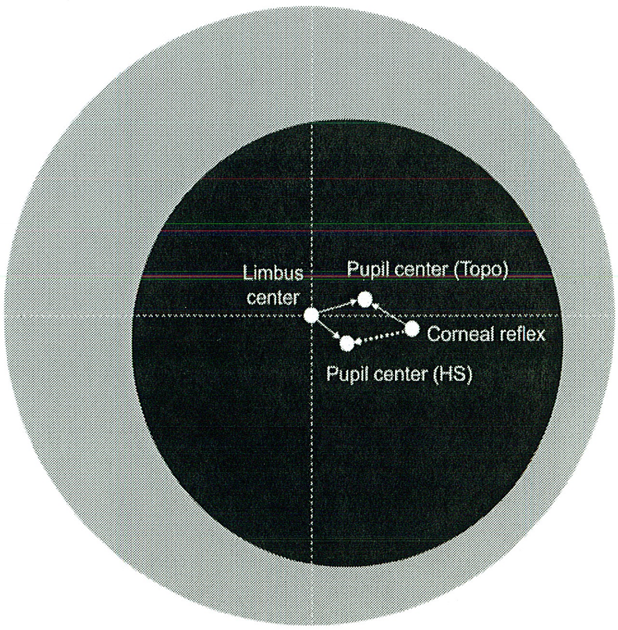

Figure 2. Schematic diagram of the several origins measured in this study.

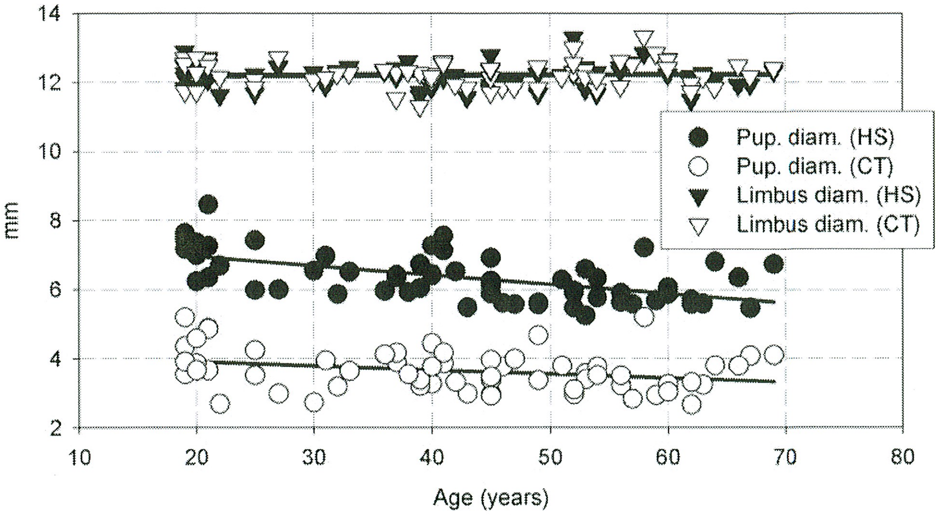

FIGURE 3. Pupil and limbus diameters as a function of age for all patients included in the study.

limbus, a fixed reference in both illumination conditions, could be calculated as explained. From this reference, the pupil center in both illumination conditions was computed (the white continuous vectors with their origins at the limbus). From the topography image, it was also possible to determine the position of the pupil with respect to the corneal reflex, which was one of the displacements required to calculate corneal aberrations centered in the pupil (continuous white vector with the origin in the corneal reflex shown in the figure).

The displacement of the pupil (under HS illumination conditions) with respect to the corneal reflex was also required (dotted white vector). This could be estimated by combining the other vectors shown in Figure 2.

A custom computer routine was used to export the elevation data directly into ray tracing software (ZEMAX Development, Bellevue, WA).[16] The resultant corneal surface was decentered using the previously calculated values of pupil decentration with respect to the corneal reflex. Ray tracing was performed through this decentered surface, and aberrations were calculated in terms of a Zernike modal expansion. Two decentrations were used, one for the pupil position provided under the topography illumination and one for the pupil position provided under aberrometry illumination.

Results

Centration

Figure 3 shows pupil and limbus diameters calculated for topography and HS illumination conditions as a function of age for the 62 patients included in this study. Lines represent linear regression fits to the data sets. Average pupil diameter was 6.4 ± 0.7 mm for images taken under HS illumination conditions and 3.6 ± 0.6 mm for images taken under CT illumination conditions. Average limbus diameter was 12.2 ± 0.4 mm for both light illumination conditions. Regression slopes underestimated to the same degree the reduction in pupil size with age because of the 5-mm diameter requirement for HS aberrometry.

Pupil center positions with respect to the corneal limbus center are shown in Figure 4 for the HS aberrometer (left) and the corneal topographer (right). There was a tendency for the pupil center shifts to be nasal-superior (to the right and upward). The tendency for nasal shift was slightly greater for the smaller pupils with the corneal topographer illumination (mean, 0.17 ± 0.12 mm) than for the HS aberrometry illumination (mean, 0.19 ± 0.14 mm), but the shifts in the vertical direction were similar (mean for both, 0.11 ± 0.16 mm). The modulus of the displacement of the pupil between the illumination conditions was computed using $\sqrt{(d_{X\_CT} - d_{X\_HS})^2 + (d_{Y\_CT} - d_{Y\_HS})^2}$, where d_{X_CT} and d_{Y_CT} were the X and Y coordinates of the pupil center with respect to the limbus center under CT illumination, and d_{X_HS} and d_{Y_HS} were the pupil center coordinates with respect to the limbus center under HS illumination. Mean value was 0.21 ± 0.11 mm.

The other relevant reference point for the study was the corneal reflex, the origin for topography calculations. Figure 5 shows the pupil center positions with respect to this point. These were the values introduced to the ray tracing routine to

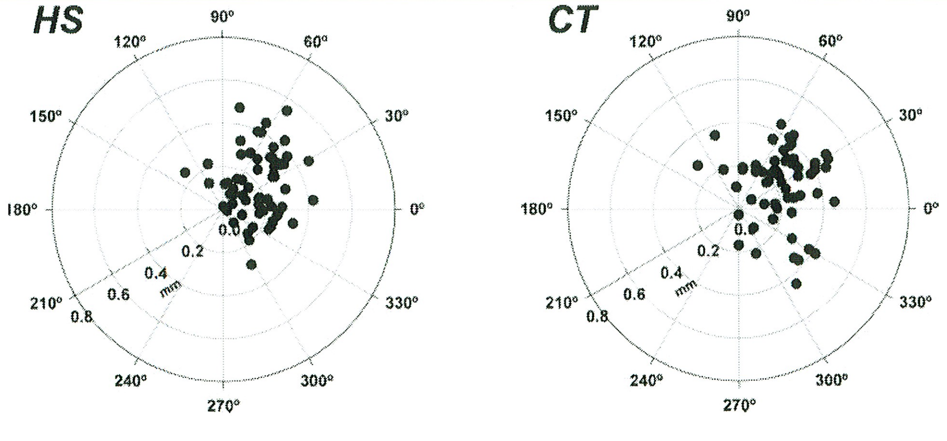

FIGURE 4. Pupil center location with respect to limbus center. *Left*: pupil is taken from the HS image. *Right*: pupil is taken from the topography image. Nasal direction is toward the *right* side.

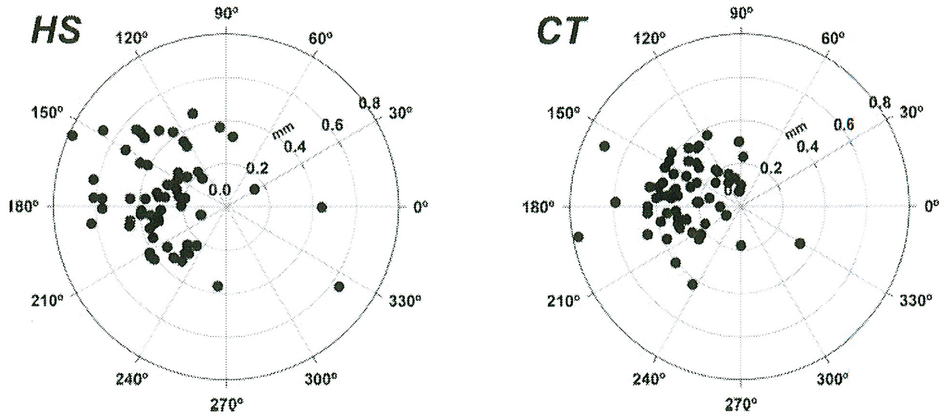

FIGURE 5. Pupil center location with respect to the first Purkinje image position (corneal reflex). *Left*: pupil is taken from the HS image. *Right*: pupil is taken from the topography image. Nasal direction is toward the *right* side.

correct for the default misalignment of the corneal reflex with respect to the pupil. Mean horizontal positions of the HS pupils and the CT pupils with respect to the corneal vertex were -0.28 ± 0.21 mm and -0.25 ± 0.17 mm temporally. Mean vertical shifts were 0.04 ± 0.15 mm and 0.05 ± 0.20 mm superiorly.

Figure 6 compares pupil centers in terms of Bland-Altman plots (plots of differences against means). Dotted lines represent the 95% confidence intervals from the average of the differences. The vertical direction showed slightly larger confidence intervals than the horizontal direction. Paired *t*-tests did not show statistical differences between *X*-coordinates or *Y*-coordinates for the two illumination conditions ($P = 0.19$ and $P = 0.75$, respectively). However, approximately 18% of the population had pupillary center differences larger than 0.3 mm.

Corneal Aberrations

Although corneal spherical aberration was expected to remain unchanged at different pupil centrations, it was appropriate to check the distribution of spherical aberration in this emmetropic population because of the implications of large spherical aberrations for the coma generated by pupil decentration. Figure 7 shows the differences between corneal spherical aberration (C_0^4; double-index OSA notation[17]) calculated under CT illumination and the corneal spherical aberration calculated with pupil centration under HS conditions, plotted as a function of the mean of the two spherical aberrations (5-mm pupils). The dashed line represents the mean of the differences, and the dotted lines are the 95% confidence intervals. Embedded in the figure is a histogram for the spherical aberration of this population under HS pupil conditions. Spherical aberration calculated under the two different centrations were highly correlated, and the differences were never larger than 0.02 μm. In addition, the distribution of spherical aberration had a peak (39% of the population) between 0.10 and 0.12 μm for a 5-mm pupil diameter. The mean value was 0.11 μm (SD = 0.03 μm). The tightness of the distribution was important because large differences in spherical aberration between subjects would make the generation of coma with change in pupil position very different from one subject to another.

Results in the differences between corneal comas calculated under the two light illumination conditions were also studied with Bland-Altmann plots (Fig. 8 left, lateral coma C_1^3; right, vertical coma C_{-1}^3). In general terms, the mean differences were nearly zero (dashed lines), indicating that any biases of one measurement with respect to the other were randomly distributed. In addition, no significant slopes were found. The 95% confidence intervals with respect to the mean were larger for vertical than for horizontal coma. Paired *t*-tests did not show statistical differences between the illumination conditions for horizontal ($P = 0.21$) or vertical ($P = 0.42$) coma.

Differences in coma between the illumination conditions were also evaluated in the histogram in Figure 9. The modulus of coma ($\sqrt{(C_1^3)^2 + (C_{-1}^3)^2}$) was calculated, and the absolute difference of this quantity between calculations in the two pupil conditions was represented in the histogram. Approximately 68% of the population had differences smaller than 0.05 μm, and only 4% had differences larger than 0.1 μm.

To determine how these differences in coma between the illumination conditions were related to the differences in cen-

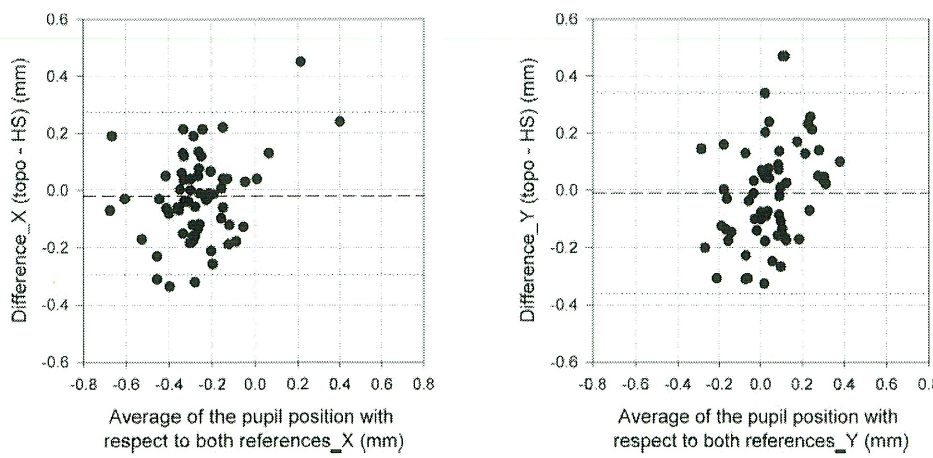

FIGURE 6. Differences between pupil positions with both methods (HS and CT) plotted as a function of the mean value of both results (*left*: horizontal coordinates; *right*: vertical coordinates). *Dashed line*: mean of all differences. *Dotted lines*: 95% confidence intervals.

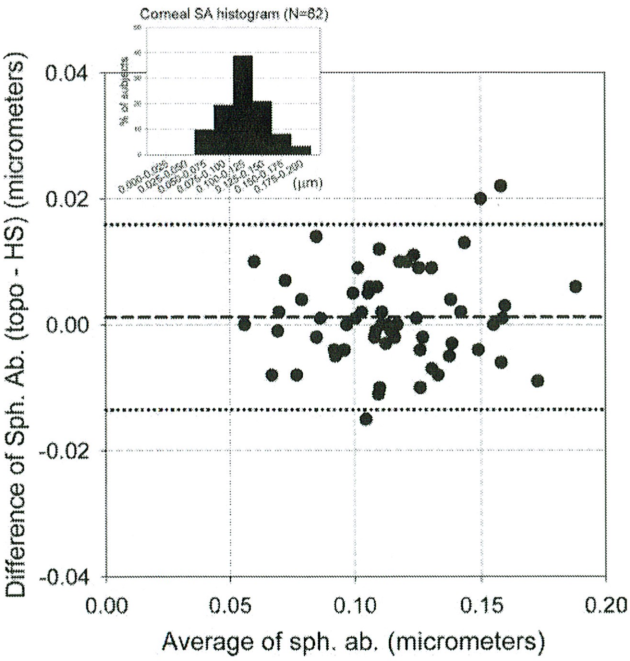

Figure 7. Differences between spherical aberration calculated with both pupil centrations (HS and CT) plotted as a function of the mean values of both results. *Dashed line*: average of the differences. *Dotted lines*: 95% confidence intervals. *Inset*: histogram of spherical aberration of our population ($N = 62$) evaluated with the HS pupil position.

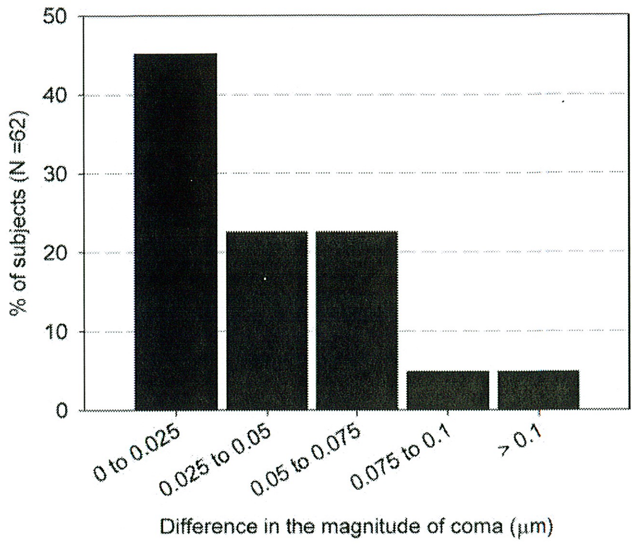

Figure 9. Histogram of absolute differences in the magnitude of coma (5-mm pupil diameter) calculated for the two different pupil decentrations.

tration, the differences in coma (topography − HS conditions) were plotted against the differences (topography − HS conditions) in centration. Figure 10 shows these plots in the horizontal (Fig. 10, left) and vertical (Fig. 10, right) directions. Correlations were high in both cases ($R^2 = 0.96$; $R^2 = 0.82$) but were clearly higher in the lateral direction than in the vertical direction. Slopes of the regressions were, as expected, similar (0.32 μm/mm in the horizontal direction and 0.33 μm/mm in the vertical direction).

Analysis of other higher-order Zernike modes in terms of correlations, Bland-Altmann plots, and paired *t*-tests did not show any significant differences between illumination conditions. Differences in aberrations were manifested primarily in the values of coma, as expected; however, even in this case, the pupil center differences were not big enough to reach statistical significance (though these differences are clearly explained by Fig. 10).

Discussion

HS aberrometry and CT were conducted under mesopic illumination and photopic illumination, respectively. Average pupil diameters under HS illumination in this study (6.4 ± 0.7 mm) were similar to those under mesopic illumination found by Yang et al.[10] (6.4 ± 0.9 mm). Pupil diameters found under CT illumination conditions (3.6 ± 0.6 mm) were slightly smaller than those of Yang et al.[10] measured under photopic conditions (4.1 ± 0.7 mm). The photopic condition they described was "with room lights on." In CT illumination, the more directional component, which provoked a more constricted pupil (the light from the Placido rings directly illuminates the eye, in contrast to fluorescent light from the ceiling), and the age differences in both groups could have played roles. However, in general we obtained similar results concerning pupil movement: the pupil tended to be nasal and slightly superior with respect to the limbus center under photopic CT and mesopic HS conditions, with the pupil slightly more centered under mesopic HS illumination.

Although previous studies[7,8] used the corneal sighting center (the corneal surface point where the line of sight is intercepted) to center the origin of corneal aberrations, we used the

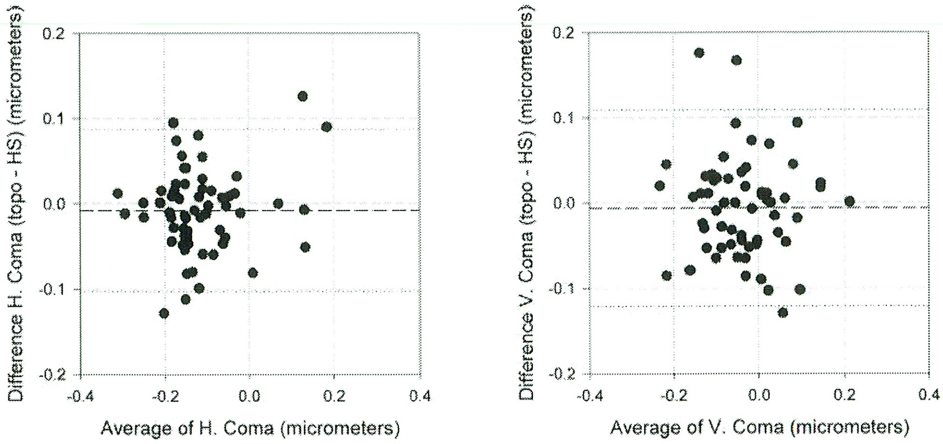

Figure 8. Differences between corneal coma calculated with both pupil centrations (HS and CT) plotted as a function of the mean values of both results (*left*: horizontal coma; *right*: vertical coma). *Dashed line*: average of the differences. *Dotted lines*: 95% confidence intervals.

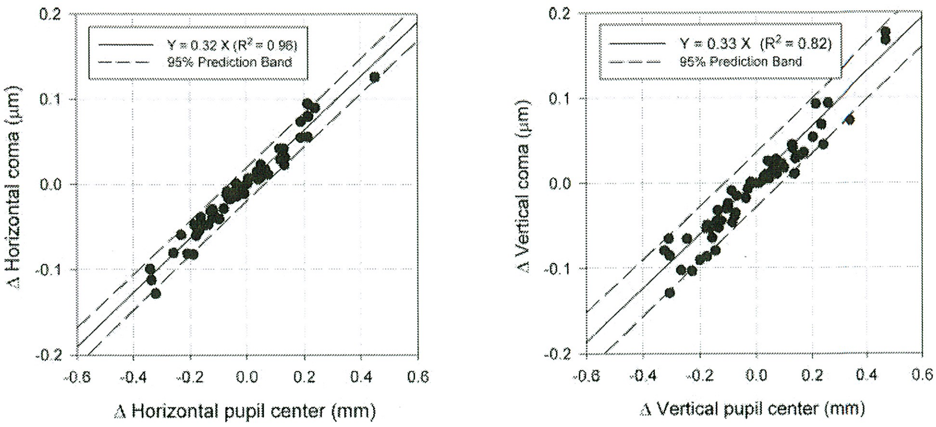

FIGURE 10. Change in corneal coma as a function of change in the pupillary decentration (CT − HS) between the two illumination conditions. *Left*: Horizontal coma. *Right*: vertical coma.

entrance pupil center for simplicity. This approximation worked well and provided similar results. If x_1 represents the position on the corneal sighting center and x_2 is the position of the entrance pupil, both referenced with respect to the corneal reflex, the following equation can be derived $x_1 = \left(\frac{SC}{SC + CP}\right)x_2$, where SC is the distance of the source to the corneal vertex and CP is the distance from the cornea to the entrance pupil (more detailed information on the geometry for this problem can be extracted from Atchison[7] and Salmon and Thibos[8]). Given that the distance of the eye to the source is 60 mm and that our subjects with emmetropia were of various ages (usually the entrance pupil position was within 3 mm of the anterior cornea),[18] it can be shown that the difference between both reference centers was less than 5%. This induced a maximum possible error for the corneal coma differences of approximately 0.011 μm, which can be considered negligible.

Our primary concern was how this difference in pupil center between illumination conditions could affect corneal aberrations. An optical system with a laterally misaligned pupil generates coma in a linear fashion because of an equivalent off-axis effect.[12] The generation of coma per millimeter of decentration depends on the spherical aberration of the system. Therefore, if corneal surfaces have large dispersions of spherical aberration, coma will be generated at many different ratios for similar amounts of decentration. However, the corneal spherical aberration distribution was compact (0.11 ± 0.03 μm for 5-mm pupils; see histogram of Fig. 7), which makes the ratio of the generation of corneal coma per millimeter of decentration relatively consistent (Fig. 10).

Direct comparison between corneal comas (Fig. 8) and between the positions of the pupil centers (Fig. 6) for the illumination conditions showed more variability for the vertical than for the horizontal meridian. This discrepancy between horizontal and vertical meridians can be also seen in Figure 10; high correlation was found for horizontal comas with horizontal shift of the pupil, whereas slightly less high correlations were found for vertical comas with vertical shifts. It may be that fourth-order and higher asymmetric aberrations weaken the relationship between coma and pupil centration in the vertical direction more than in the horizontal direction.

Recent studies[19-22] have been concerned with the natural compensation of corneal coma by the internal optics of the eye. According to the change of coma that occurred because of the pupillary shift measured in this study, the effect on the internal aberration calculations was small enough not to alter any general conclusion of studies that used CT and HS aberrometry measured separately[7,19,21,22] (changes in internal aberration were equal and opposite in sign to changes in corneal aberration). If precise values are required, the pupillary shift resulting from the different illumination conditions occurring with both instruments should be taken into account when calculating corneal coma aberration.

This effect may be dangerous in corneal surgery. However, under both illumination conditions, differences greater than 0.3 mm between pupil centers were observed in only 4 of 62 subjects along the horizontal direction, and differences greater than 0.3 mm were observed in 6 of 62 subjects along the vertical direction. Decentration of 0.3 mm could be well within the range for surgical improvement. According to Bueeler et al.,[23] decentered customized corneal refractive surgery will not significantly degrade the optical quality of the eye with respect to its quality before surgery unless the decentration exceeds 0.45 mm (results based on a 7-mm pupil diameter). However, the fact that optical quality does not decay under a certain limit does not mean that the performed wavefront-guided surgery is successful. Decentrations will always constitute one of the drawbacks to achieving a perfect wavefront-guided correction. A precision of 0.07 mm is required to achieve the diffraction limit optical quality (criteria based on a 7-mm pupil diameter. It becomes 0.2 mm for a 3-mm pupil diameter). As can be seen from the differences in Figure 6, 0.07-mm decentration was surpassed by most of our subjects, indicating that the diffraction limit may not be achieved in a healthy population, depending on illumination level and subsequent pupil size.

Pharmacologic pupil dilation can also account for centration errors resulting from shifts in pupil center with respect to natural conditions.[10,24,25] This may depend on the kind of drug used for dilation. Porter et al.[24] measured a different systematic direction of pupillary shift with phenylephrine (Neo-Synephrine; inferonasal) than did Yang et al.[10] with cyclopentolate (superotemporal).

IOLs that correct the positive spherical aberration in the eye may be affected by pupil center shift. However, the typical age of the patient undergoing cataract surgery is less problematic than that of the corneal refractive surgery patient because the mesopic pupil tends to be smaller in older than in younger patients (Fig. 3). Tabernero et al.[16] established ranges of decentration under which spherical aberration-correcting IOLs provide optical benefits compared with conventional spherical IOLs. In the horizontal direction, this was from 0.2 mm nasal to 0.8 temporal (the asymmetry is attributed primarily to the angle κ and to a realignment effect with decentration). If the pupil moves in the nasal direction from mesopic to photopic conditions, the IOL tends to be temporally decentered with respect to the center of the pupil. Therefore, according to these limits, the typical pupillary shift measured in this study seemed to be within the estimated tolerance limits.

In conclusion, a precise set of data of the pupillary shift under two illumination conditions (from two typical clinical instruments) was presented in this study. The effect of the pupil shift in aberrations was evaluated, and, though it seems that the change in optical quality was small for the primary population, a few subjects (7 of 62; 11% of the population measured) had a significant shift (magnitude) larger than 0.25 mm. The effect of these errors will not make custom corneal refractive surgery and spherical aberration-correcting IOLs worse than conventional treatment for most patients, but they reduce the potential optical benefit.

Acknowledgments

The authors thank Robert Iskander for help with computer routines and for comments and suggestions on this work.

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